Proposal to Design Integrated Sensors

Submission: 21 June, 2019

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Abstract: In the context of the TOPSiDE detector concept, we propose to design silicon sensors with integrated front-end readout. The sensors are based on the Low-Gain Avalanche Diode (LGAD) technology and feature ultra-fast signals, as required by TOPSiDE's particle-identifying, imaging calorimeter.

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Introduction: TOPSiDE

TOPSiDE [1] is a modern EIC detector concept based on novel detector paradigms and technologies recently developed by the High-Energy and Nuclear physics community. The tracking of charged particles is achieved with a precision vertex detector and a five-layer silicon tracker in the barrel region, supplemented with forward disks. The calorimeter is imaging, i.e. it features extremely fine granularity, both laterally and longitudinally. The particle identification (pion-kaon-proton separation) is achieved through precision timing in the calorimeter. In the very forward (hadron) region, the detector features a Ring Imaging Čerenkov counter (RICH), a dipole magnet, additional tracking disks, and again imaging calorimetry. In the backward (electron) direction, the required energy resolution is achieved by a crystal calorimeter, also with fine granularity. The central solenoid with a field of three Tesla is placed outside the calorimeter.

Advantages to this approach are many: Each particle produced in ep/eA collisions is measured individually with the subdetector providing the best momentum/energy resolution (Particle Flow paradigm) [3]; the energy resolution for neutral, hadronic particles can be improved through software compensation techniques [4]; due to the imaging capability of the calorimeter, a muon identification system becomes redundant; the material in front of the calorimeter is minimized, as there is no need for additional time-of-flight counters, Čerenkov counters or Transition Radiation Detectors; last but not least, the output of the detector is a list of identified particles with their momenta, similar to the hadron level output of Monte Carlo simulations.

The advantages for physics are many as well: higher photon detection efficiency (due to the minimal amount of 'dead' material in front of the calorimeter and hence an improved material budget. This is particularly important for the measurement of the DVCS process); improved kinematic reconstruction, in particular when using the double angle or Jacquet-Blondel method, jet reconstruction, and background rejection (due to the excellent reconstruction (energy and angle) of the hadronic system), etc. The superior reconstruction capability of TOPSiDE will result in an optimal use of the luminosity and provide precision measurements for all physics processes of interest at the EIC.

Introduction: Ultra-fast Silicon Detectors

The TOPSiDE concept requires Ultra-fast Silicon Detectors (UFSDs) with excellent timing resolution. GEANT4-based Monte Carlo simulations of TOPSiDE showed that a resolution of 10 picosecond or better is required to distinguish pions and kaons up to 7 GeV/c (the range of momenta for most of the solid angle).

UFSDs are being developed by various groups worldwide [5]. Currently, the best performance achieved a time resolution of 18 picosecond [6]. This was obtained with 35 μm thick sensors based on the Low-Gain Avalanche Diode (LGAD) technology and read out by an external digitization system.

To further improve on these results, we propose to incorporate the readout system (digitization) into each pixel of the sensor. Apart from the expected improvement in time resolution, this will result in a significant cost savings for the final production and assembly.

Research program

In the following we detail the UFSD research program at Argonne. This is an ambitious and long-term endeavor including a number of subtasks which can be in part executed in parallel. Several items are already completed or already ongoing. This proposal applies mainly to items f and g:

a) Testing of silicon sensors

We acquired the necessary tools for testing UFSDs on the bench (GigaHertz oscilloscope, DC power supplies, signal processing computer, environmental chamber, and mechanical stands). We performed measurements of the IV and CV curves on several UFSDs obtained from collaborators at Torino, Santa Cruz, and BNL. We tested pairs of sensors in the Fermilab test beam to establish their time resolution. As an example, Fig. 1 shows the waveforms obtained from an HPK sensor in the primary 120 GeV proton beam. This is an ongoing effort with many more test beam campaigns expected in the future.

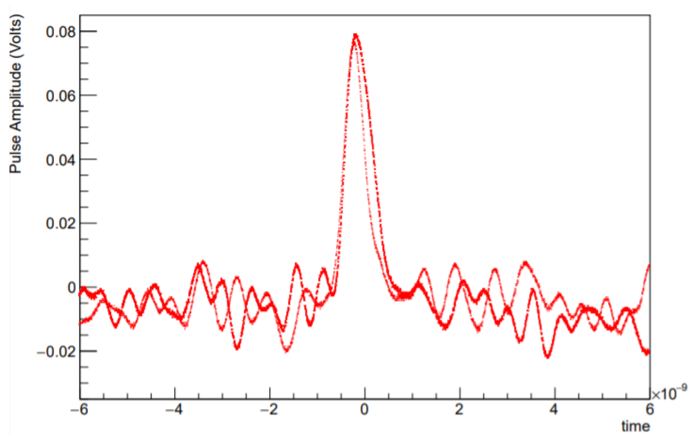


Figure 1. Waveforms recorded with an HPK sensor in the Fermilab test beam.

b) Development of a readout scheme

We developed a readout scheme for UFSDs (see Fig. 2), to be eventually implemented into each pixel. The signal from a given pixel is being shaped, amplified and its time-of-arrival as well as its time-over-threshold is being measured. To obtain the best possible time measurement a constant fraction discriminator is utilized, based on work performed by University of California Santa Cruz.

c) Design/simulation of an LGAD sensor

We completed the design/simulation of an LGAD sensor in terms of the physics of the silicon device, see Fig. 3. The sensor features the mandatory amplification layer responsible for the excellent timing characteristics with 1 x 1 mm^2 pads. Studies of the doping concentration, guard rings, temperature dependence etc. were performed with a commercial EDA tool called Silvaco™ ATLAS. Additional details about the design are given below in the section answering the advisory committee's specific questions.

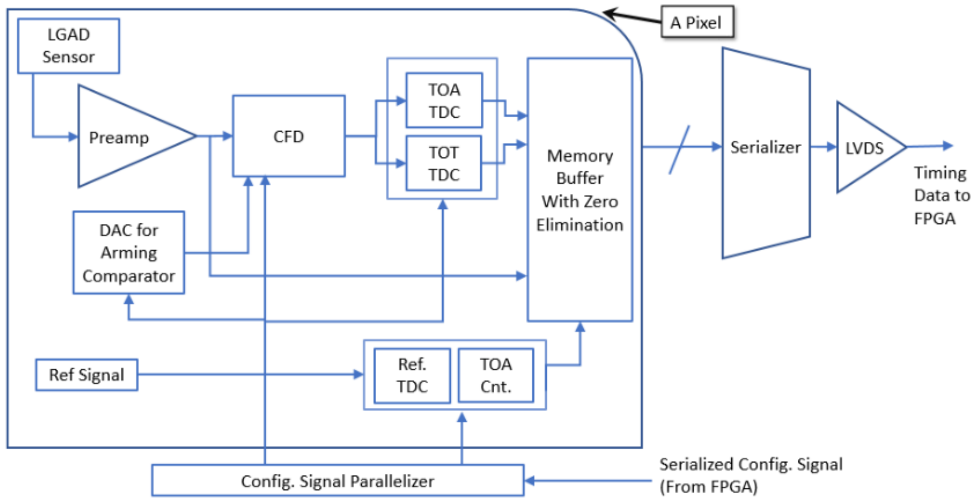


Figure 2. Schematic of the electronic readout to be implemented for every pixel.

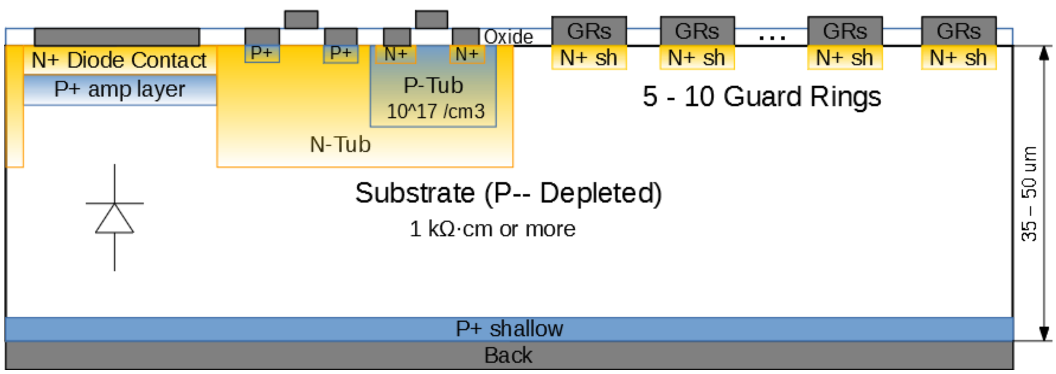


Figure 3. Design of the Argonne UFSD.

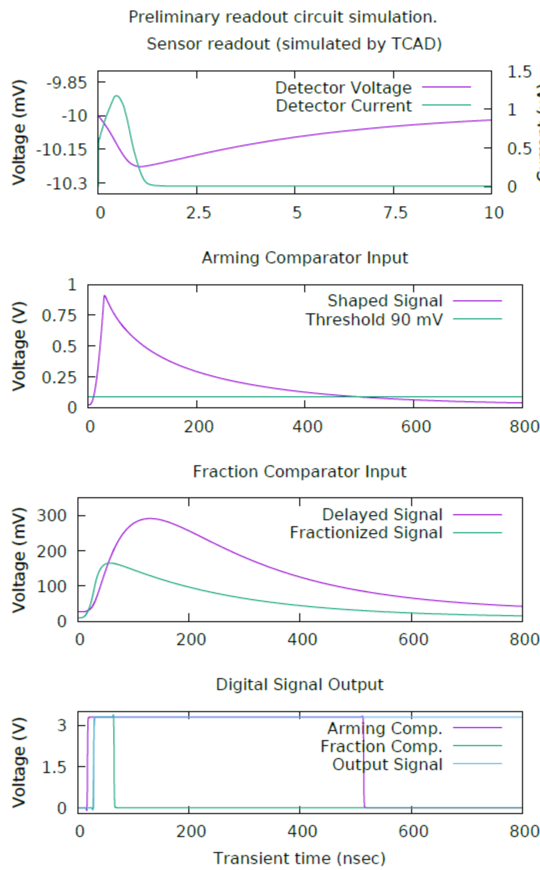
d) Implementation of the 1st stage of the readout system

The first stages of the readout system are being prototyped with discrete components on a PCB board. The first stages include the multiple stage preamplifiers, a shaper with four programmable delays, and the discriminators. The circuitry has been fully simulated, see Fig. 4 a). Schematics of the circuitry and layout of the board are complete, Fig. 4 b) – d), and the board has been fabricated and is currently being assembled.

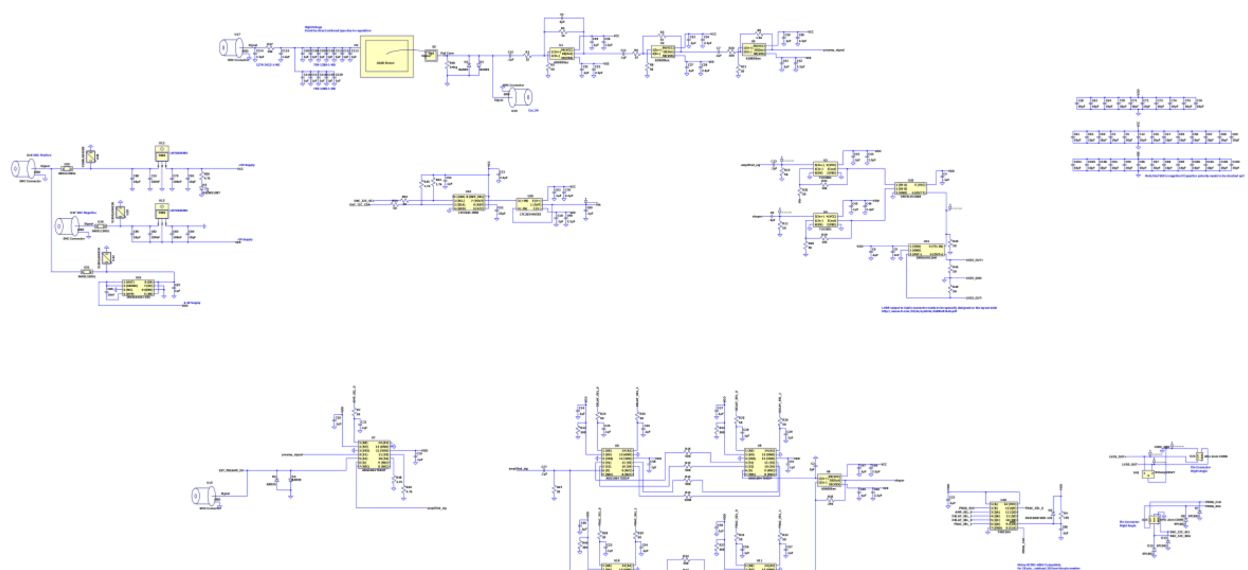
e) Testing of sensors with the 1st stage of the readout system

Sensors will be tested with the prototype of the 1st stage of the readout system. These tests will include measurements with sources as well as data taking in the Fermilab test beam. At this stage, the TDC circuitry and logic is implemented through an FPGA toolkit, ZedBoard C-grade, based on Xilinx Zynq 7000 SoC.

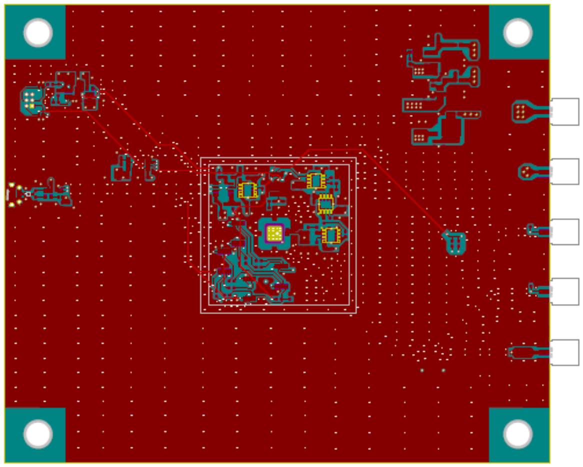
f) **Implementation of the 1st stages of the readout system onto the sensor**


Preliminary readout circuit simulation.
Sensor readout (simulated by TCAD)
Voltage (mV)
Current (μA)
Detector Voltage
Detector Current
-9.85
-10
-10.15
-10.3
1.5
1
0.5
0
0
2.5
5
7.5
10
Arming Comparator Input
Voltage (V)
Shaped Signal
Threshold 90 mV
1
0.75
0.5
0.25
0
0
200
400
600
800
Fraction Comparator Input
Voltage (mV)
Delayed Signal
Fractionized Signal
300
200
100
0
0
200
400
600
800
Digital Signal Output
Voltage (V)
Arming Comp.
Fraction Comp.
Output Signal
3
1.5
0
0
200
400
600
800
Transient time (nsec)

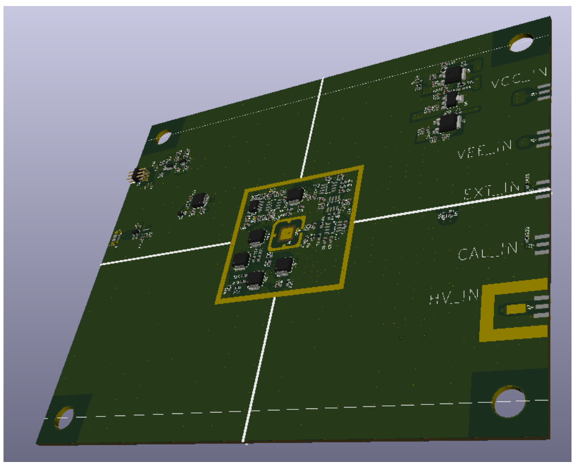
(a)



(b)



(c)



(d)

Figure 4. (a) Simulation of the shaping, amplification and discriminator circuits. (b) Schematic diagram of the discrete component based CFD circuitry. (c) The PCB layout of the CFD-board. (d) 3D rendering image of the CFD-board, generated from KiCAD.

After careful testing of the prototype of the 1st stages of the readout system, its schematic will be implemented onto the sensor. This requires identification of a foundry, such as LFoundry, AMS, or Towerjazz, able to process LGAD sensors with implemented HVCMOS circuitry. As Argonne does not have the necessary EDA software licenses for the mask design and transistor level VLSI circuit simulation, this design work will be performed at Fermilab. Initial discussions about collaborating with Fermilab already took place with Gary Drake (senior engineer). Similar discussions took place with Ivan Peric from Heidelberg (AMS foundry CMOS design).

There are particular challenges to be faced when implementing the 1st stages of the electronic readout onto the sensor: identifying a foundry which is compatible with our integrated sensor design; the sensors being extremely thin (around 50 μm) and requiring processing on both sides without the use of a carrier wafer, risking a reduction of the overall yield; the thickness of the sensor also requires extremely careful mechanical handling, as the wafer will be quite brittle; the doping concentration of the amplification layer is required to be very uniform, imposing a particular challenge onto the fabrication process.

g) **Prototyping of sensors with the 1st stages of the readout system**

After the successful completion of the design of a sensor with implemented 1st stages of the readout system and after a thorough internal design review, the sensor will be prototyped in small quantities and undergo extensive testing. To reduce cost of the prototype fabrication, the production will be shared with other institutes in a multi-project wafer run.

h) Final design and prototyping steps (beyond the first year of funding)

The further steps in the development of integrated sensors include the implementation of the complete readout system, including the TDCs (time-to-digital converters) and the serializer (located on the rim of the sensor), on the HVCMOS device, and the subsequent prototyping and testing. In parallel to this work, we plan to develop a time distribution system with extremely low jitter, less than 10 picoseconds. This work is planned in collaboration with institutes in Italy (Bologna and Torino).

Finally, in the long-term, sensors with a large channel count will be designed and produced for assembly in a small-scale prototype electromagnetic calorimeter, dubbed the PENTACAL. The latter will undergo tests in the Fermilab test beam.

Deliverables

The major deliverable of this proposal is a tested sensor with the 1st stages of the readout system implemented in HVCMOS. It will be used to

- Set performance benchmarks with the prototype
    - Time resolution
    - Jitter
    - Tracking efficiency
- Identify remaining technical challenges
- Identify potential vendors and cost for large scale applications

Funding request

We request support for postdoctoral research assistants in the amount of $125k (Manoj Jadhav 0.5 FTE and Taylor Shin 0.5 FTE, see below). The major task of the postdocs will be the implementation of the 1st stages of the electronic circuitry into the sensor. The proposed work will be carried out at Fermilab which possesses the necessary software tools. Funds are requested for the prototyping of the 1st iteration of the integrated sensor ($30k).

The postdoctoral research assistants will be supervised by José Repond and Jessica Metcalfe.

	Personnel funds	Prototype fabrication	Sum
Argonne National Laboratory	$125k	$30k	$155k

Table I. Summary of funding requests.

The Argonne team

We have assembled a competent team to carry out the project:

José Repond: team leader
Leader in several past projects (ZEUS Barrel calorimeter construction, Small angle tracker for ZEUS, Digital Hadron Calorimeter). Particularly relevant for this proposal is his experience with ASIC design (DCAL chip) and calorimetry.

Jessica Metcalfe: silicon expert consultant
U.S. deputy project manager for the ITk pixel upgrade of ATLAS. L3 manager for the silicon pixel Modules for international ATLAS ITk pixel. 15 years of experience with silicon detectors.

Manoj Jadhav: postdoc working on silicon testing
Experience with fabrication and testing of silicon sensors.

Taylor Shin: postdoctoral electronics engineer
Experience with the design of various silicon sensors, including fast sensors for X-ray physics and the current Argonne LGAD sensor. Experience in designing ASICs.

Argonne recently commissioned the Argonne Micro Assembly Facility (AMAF), a class 10,000 clean room with 4,200 square feet. The goal of the AMAF is to establish cooperation across the various divisions at Argonne with interest in silicon sensor development. Modules for the ATLAS upgrade inner tracker ITk will be assembled in this facility.

<u>Additional information requested by the advisory committee</u>

1) Demonstration of clear advantage of this technology:

A full demonstration of the advantages of imaging calorimetry requires detailed simulations and complete event reconstructions, including the application of particle flow/identification algorithms. We are working on completing this chain of tools for TOPSiDE, but have not yet finished the task. (It took the ILC community the better part of a decade to achieve this. Nevertheless the corresponding hardware developments were initiated years before.)

In the meantime, we generated and simulated the decay of exclusive J/psi and Upsilon mesons into pairs of both electrons and muons. We reconstructed satisfactorily the momentum transfer variable $-t = p_T^2$ for photoproduction events, see Fig. 6. However, the reconstruction of -t for $Q^2 > 1$ GeV^2 (deep inelastic scattering) requires more work, as the momentum of the scattered electron with its low-p_T needs to be measured precisely and is an input in the calculation of -t. The measurement of the scattered electron requires both excellent tracking and calorimetry with outstanding energy resolution. We are currently working on optimizing the ECAL absorber structure, to accommodate the low energy range of particles at the EIC. Eventually, we will study hadronic decays of the Upsilon meson to demonstrate the power of 5D calorimetry, as traditional tracking/calorimetry will not be adequate to reconstruct the mass of hadronic Upsilon decays.

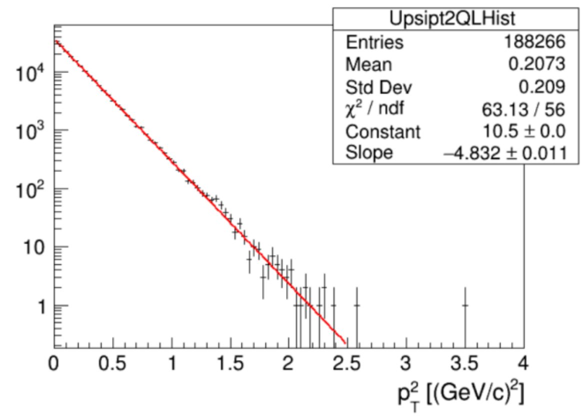


Figure 6. Reconstruction of $-t = p_T^2$ for photoproduced, exclusive Upsilon mesons decaying into pairs of electrons and measured by TOPSiDE. The input slope of the distribution was b = -4.5.

In an earlier study, we generated inclusive deep inelastic scattering events using a given set of parton density functions (PDF), corrected the data using a set of simulated events based on a different PDF, and finally reconstructed a 'measured' $F_2(x,Q^2)$ structure function. As an example we show in Fig. 7 the reconstructed versus generated momentum transfer Q^2, based on the electron method. Here, scattered electrons were identified through the characteristic shape of their showers as measured with the electromagnetic calorimeter, thus utilizing the imaging capability of the calorimeter. In general, the reconstruction is excellent. However, with optimization of the tracker layout and the calorimeter absorber structure we expect further improvements in the kinematic reconstruction.

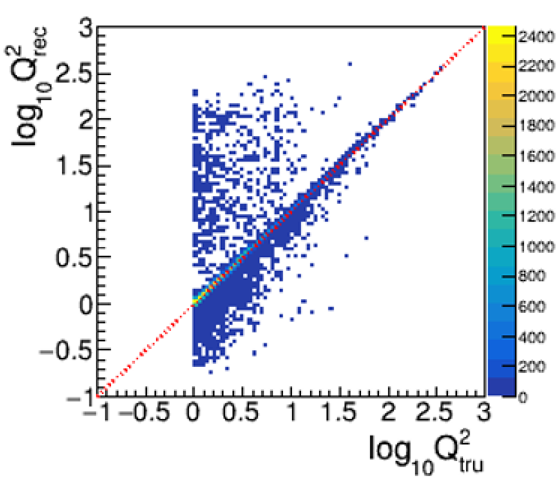


Figure 7. Reconstructed versus generated momentum transfer squared of simulated inclusive deep inelastic scattering events in the TOPSiDE detector.

2) Specifications of the sensor:

We performed detailed detector simulations, based on the TOPSiDE concept to establish the requirement on the timing resolution of the silicon sensors placed in the calorimeter. The results showed that with a resolution of 10 picoseconds pions, kaons, and protons can be identified for momenta up to about 7 GeV/c, see Fig. 8. At the EIC, this covers the entire momentum range of produced particles for most of the solid angle.

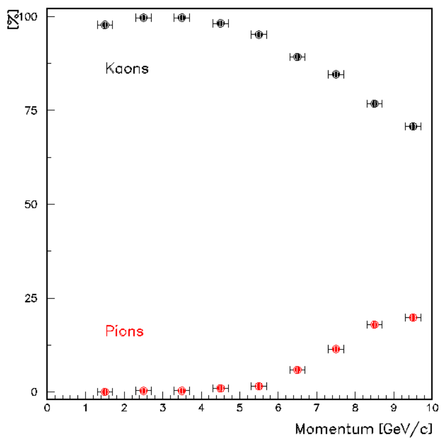


Figure 8. Particle identification assuming 10 picosecond timing resolution in the electromagnetic calorimeter showing kaons identified as kaons and pions mis-identified as kaons. This result is based on the full simulation of TOPSiDE.

During the past year or so, Argonne completed the design of its own sensor [1] using the Silvaco™ ATLAS simulation tools [7]. The sensor is nominally 50 µm thick and features 1 x 1 mm^2 pixels (the pixel size is defined by the current technical feasibility). At the edge of the sensor five guard rings reduce the voltage drop to increase the breakdown voltage. The operating voltage is around 200 V. All relevant performance parameters were studied, starting with the mapping of the electric fields and the establishment of the breakdown voltage. As an example, Fig. 9a left (right) shows the dependence of the leakage current (signal current) on the operating temperature. Note that operating at say -20 ^{0}C offers two distinct advantages: a significantly reduced leakage current and an enhanced signal current.

As a further example, Fig. 10 left (right) shows the leakage (signal) current as function of doping concentration for different operating temperatures. Independent of operating temperature, concentrations in excess of 1.5 x $10^{17}/cm^3$ lead to unacceptably large leakage currents.

Cooling of the sensors is of course a real issue. Assuming a similar power consumption as measured with the PicoTDC chip offering a 12 ps time resolution [8], we will need to cool approximately 0.6 – 0.7 W/cm^2. This will require additional layers of Copper plates with active cooling, as Tungsten turns out to be a poor heat conductor.

3) System requirements for an imaging calorimeter:

Imaging calorimeters preserve the separation into electromagnetic and hadronic sections. The former is optimized for the measurement of photons, while the latter provides the best possible energy resolution for the measurement of neutral hadrons (neutrons and K_L^0). The fine granularity ensures that showers are measured individually and that the classification of showers as originating from charged particles or neutral particles is not plagued by so-called confusion.

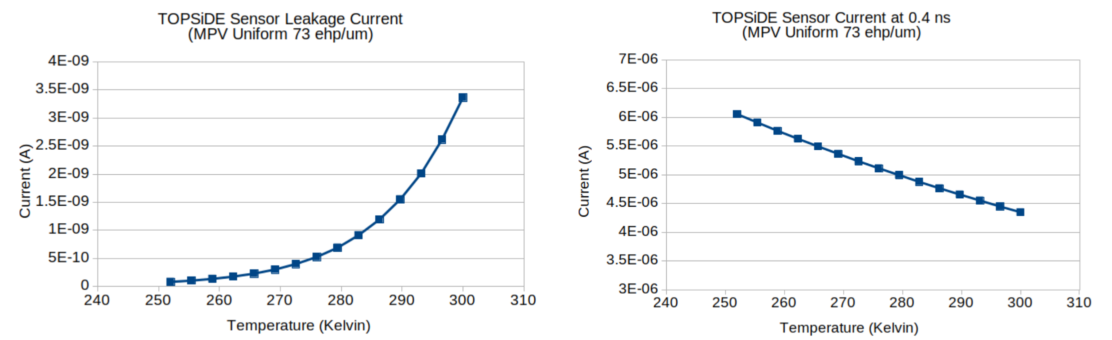


Figure 9. Temperature dependence of the a) leakage and b) signal current.

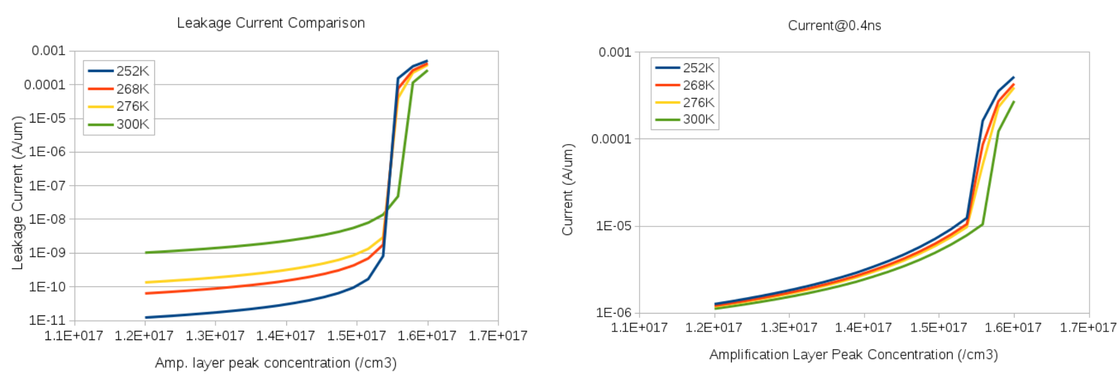


Figure 10. Dependence of the leakage current (left) and signal current (right) on the doping concentration. The different colored curves correspond to different operating temperatures.

The TOPSiDE electromagnetic section (currently) counts 20 layer, with tungsten plates as absorbers. Since tungsten is a poor heat conductor, additional Copper plates might have to be introduced to channel the heat to the edge of the modules. The absorber structure will be optimized to achieve an electromagnetic energy resolution $\sigma_E/E < 15\%/\sqrt{E}$. For most of the solid angle the pixels will be relatively large, 1 x 1 cm^2. In the very forward direction, smaller pixels might be needed to provide the best possible separation of individual particles and their showers in highly boosted jets (high-x physics).

Precision timing layers with 1 x 1 mm^2 pixels will be interspersed within 'normal' calorimeter layers with the coarser segmentation of the readout. To identify low momentum particles, which might not reach the back of the ECAL, a timing layer in the front of the calorimeter is needed, while a layer towards the back will provide, due to the longer path length, the best particle identification for particles with higher momentum.

We consider two options for the active medium of the hadronic section: a) scintillator pads (3 x 3 cm^2) [4] or b) Resistive Plate Chambers with 1 x 1 cm^2 readout pads [9]. The advantage of the former is its superior energy resolution, while the latter provides finer segmentation. The active elements will be interleaved with Steel absorber plates, typically one radiation thick each. The total depth of the calorimeter will be of the order of five hadronic interaction length.

A sketch of the TOPSiDE detector concept is shown in Fig. 11.

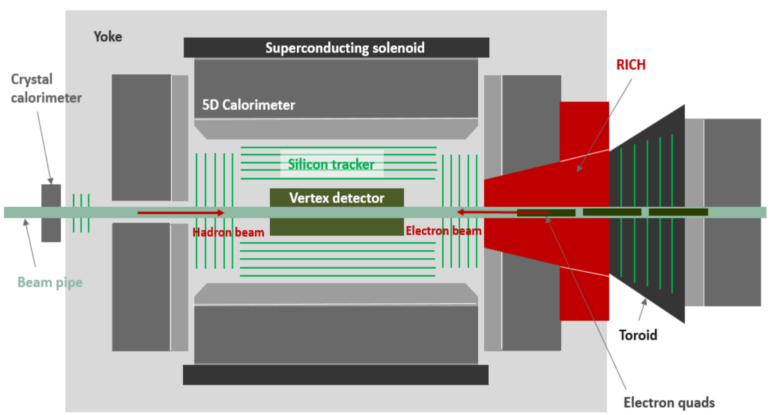


Figure 11. Sketch of the TOPSiDE detector concept.

4) Added value to ongoing efforts in the community:

We are proposing to implement the electronic readout circuitry, i.e. digitization, into each pixel. This is expected to improve the timing resolution, but also to reduce significantly the production and assembly cost for large systems. This is a unique effort and to our knowledge is not being pursued by any other group in the UFSD-community. Despite its uniqueness, we are collaborating with a number of other groups with shared interest in fast silicon, such as UC Santa Cruz, Torino, Geneva (with regular video meetings), Fermilab, Chicago, etc.

Furthermore, we are currently testing sensors obtained from various collaborators (including BNL) and are able to provide valuable information on their performance. As an example Fig. 12 shows the time difference between two sensors placed in the Fermilab 120 GeV primary proton test beam. The measured time resolution is consistent with measurements on similar sensors performed by other groups.

5) Experience and strength of the team:

See information under 'Argonne team' above.

Also, note that we will work closely with the ASIC designers at Fermilab, with whom we have established a long-term working relationship. The latter started in 2009 with the design of the DCAL chip for the Digital Hadron Calorimeter DHCAL [10].

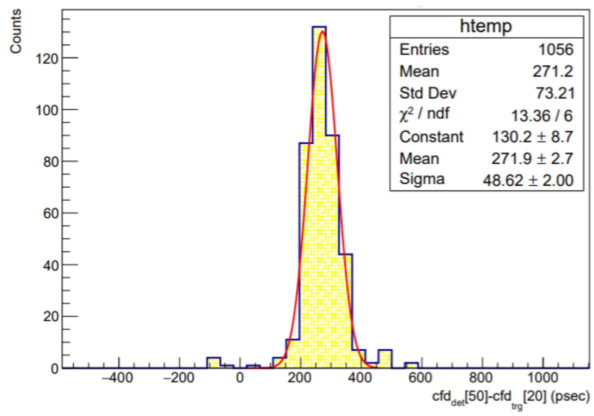


Figure 12. Time difference between two sensors in the Fermilab primary proton test beam.

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